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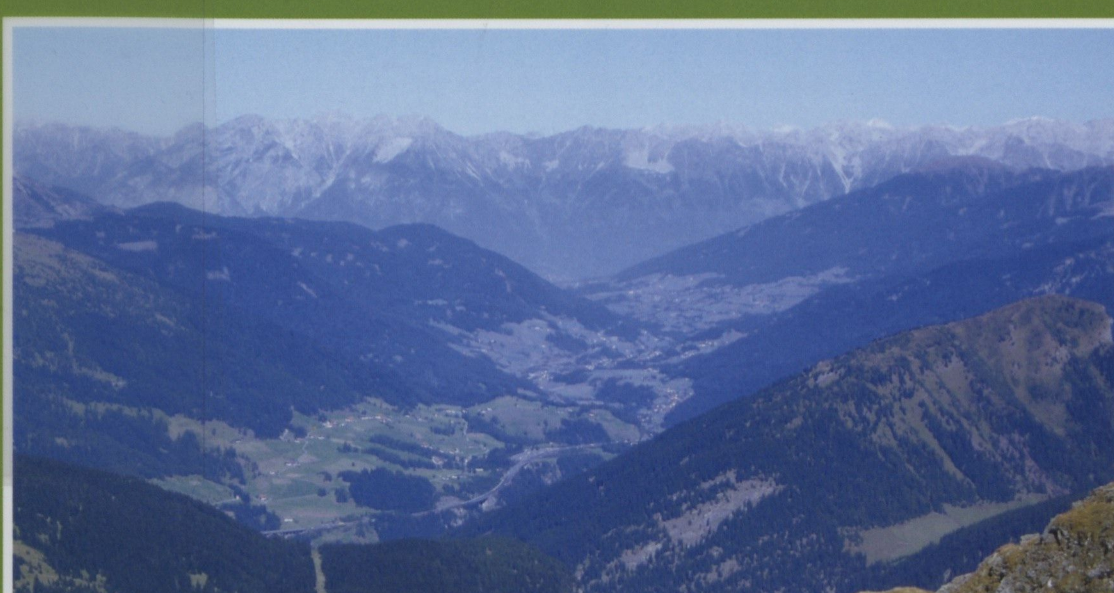
BERNHARD FÜGENSCHUH & PETER TROPPER

Transect through the Eastern Alps: Petrology and geology in the surroundings of the Brenner base tunnel

IMA2010 FIELD TRIP GUIDE AT2



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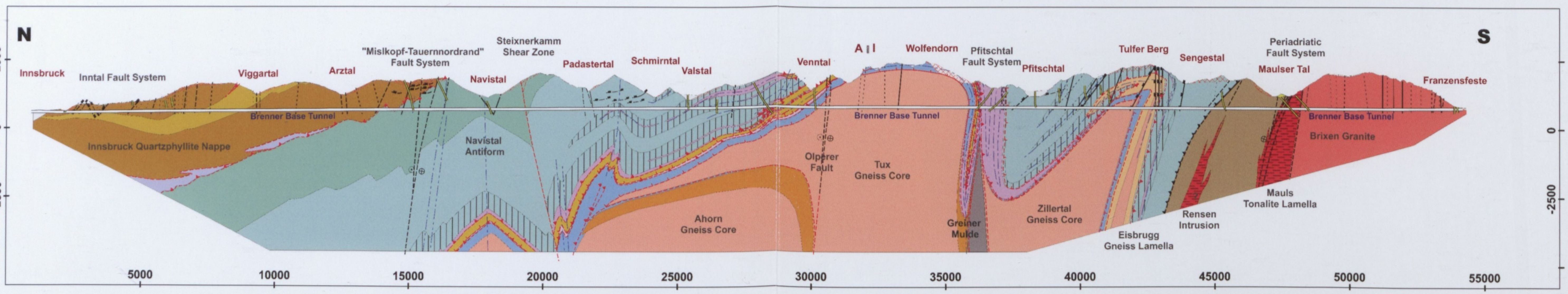
On the cover: View towards North from Brenner pass area showing the Brenner fault (valley) together with the Tauern window footwall (right side) and Ötztal hangingwall (left side). Northern Calcareous Alps in the background.

Geological cross section along the planned Brenner Base Tunnel

Töchterle, A., Brandner, R., Pomella, H. & Reiter, F.

GEOLOGY & PALEONTOLOGY INNSBRUCK



Tectonic units and marker units

- Quaternary
- Patscherkofel Basement Unit
- Innsbruck Quartzphyllite
- Innsbruck Quartzphyllite, higher metamorphic
- Tarntal Permo-Mesozoic Units
- Bündnerschiefer undifferentiated
- Upper Bündnerschiefer ("Tauernflysch")
- Lower Bündnerschiefer
- Triassic at the base of the Lower Bündnerschiefer
- Kaserer Fm.
- Hochstegen Fm. (Upper Jurassic), kyanite-quartzite (?Middle Jurassic)
- Aigerbach Fm. (Triassic)
- Wustkogel Fm. (Permo-Triassic)
- Central Gneiss and "Altes Dach" (Variscan basement)
- Furtschagl schists
- Tulfer-Senges Unit and Greiner Series
- "Maulser Trias" (Austroalpine Permo-Mesoz. U.)
- Austroalpine basement south of the Tauern Window (incl. quest. U. Carboniferous)
- Oligocene calcalkaline intrusives
- Brixen Granite

Structures

- brittle fault
- ductile fault
- fault inferred
- remote sensing
- major fault
- minor fault
- reverse fault
- strike-slipe (oblique) fault
- detachment
- thrust fault
- axial plane - gently and tight fold
- axial plane - isoclinal fold

Mass movements

- deep-seated gravitational slope deformation

Drillings (partly projected)

- Drillings (partly projected)

The shallow part of the sectionis based on the partly revised longitudinal section 1:10.000 for the Brenner Base Tunnel (Phase II). This was a consortium project of the Austrian Geological Survey, the Institute for Geology and Paleontology from the University of Innsbruck and the "Consorzio Ferrara Ricerche". We are very gratefull to the Brenner Base Tunnel Company (BBT SE) for funding this project.

Fig. 1. Transect through the Eastern Alps showing the Brenner base tunnel traverse (from Brandner *et al.*, 2008)

Geological cross section along
the planned Brenner Base Tunnel

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ACTA Mineralogica Petrographica

Transect through the Eastern Alps: Petrology and geology in the surroundings of the Brenner base tunnel

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1. Introduction

The visited area highlights the polyphase tectonic and metamorphic evolution of the eastern Alps along the Brenner base tunnel transect (Fig. 1). While the Austroalpine units bear substantial information related to the Cretaceous evolution/orogeny, the Tauern window exposes units and rocks of European provenance, metamorphosed and deformed during Tertiary collision. With additional stops in the Southern Alps the excursion provides insight in the pre-Alpine evolution of this area. During the Neogene the final shaping of this area occurred in the context of lateral extrusion and exhumation.

2. Tectonic and metamorphic evolution

The Permian evolution of the eastern Alps is highly influenced by magmatic activity represented by both, intrusive and extrusive rocks. This activity plays a key role in the Mesozoic evolution of this area, characterized by the opening of Neotethys in the east and a continuously subsiding passive margin, surrounding the Neotethys embayment. While in mid-Jurassic times the Alpine Tethys opened in the west (central Atlantic rifting), the Neotethys ocean underwent a complex evolution of subduction/obduction and re-rifting, starting in the late Jurassic (Fig. 2). It is this late Jurassic/early Cretaceous subduction in the context of which the Austroalpine units underwent metamorphic overprint up to eclogite-facies conditions. While the proper suture of this event is currently not exposed (most likely to be found under the Neogene Pannonian basin), the eclogite corridor of the eastern Alps marks the trace of the intrabasement collision between the two opposing sides of the former embayment. Cretaceous collision and metamorphism in the eastern Alps was followed by late Cretaceous extension and exhumation of high-grade rocks. This phase is well known in the Alps but also in the Carpathians and Dinarides as the Gosau phase, which marks the end of the Cretaceous cycle in the eastern Alps. The further evolution is triggered by subduction of the Alpine Tethys and final collision of the European and Adriatic plate in the Tertiary. In the course of the Tertiary orogeny the European lower plate was partly subjected to eclogite-facies metamorphism.

In the Eastern Alps, the Austroalpine basement typically shows polymetamorphism due to a sequence of metamorphic overprints, affecting this part of the Alps (Oberhänsli *et al.*, 2004; Schuster *et al.*, 2004). The most dominant metamorphic overprints are the Variscan- and the Eo-Alpine metamorphic event (Hoinkes *et al.*, 1999; Neubauer *et al.*, 1999; Thöni, 1999). In recent years, geochronological data also point to a widespread Permian thermal overprint mainly observed in the eastern part of the Austroalpine units (Schuster *et al.*, 2001). Since Paleozoic times it was affected by four regional metamorphic events (Oberhänsli *et al.*, 2004, Schuster *et al.*, 2004) in Late Devonian to Carboniferous, Permian, Cretaceous and Oligocene to Miocene times. The Late Devonian to Carboniferous imprint is related to the Variscan orogenic cycle. In Permian times large parts of the Austroalpine units were affected by lithospheric extension and related high-temperature/low-pressure metamorphism. The Eo-Alpine tectonothermal event in the Cretaceous is due to intracontinental shortening within the Austroalpine unit. Finally in Oligocene to Miocene times a thermal influence of the Alpine metamorphic event, related to the continental collision after the closure of the Penninic oceans can be recognised in the tectonically lowermost Austroalpine units to the south of the Tauern Window.

Based on their position within the Alpine orogen the individual lithostratigraphic units of the Austroalpine unit experienced different metamorphic histories during these four metamorphic events mentioned above. Most of the units are polymetamorphic, but several of them experienced only one imprint: e.g. in the Silvretta-Seckau-, Ötztal-Bundschuh- and Drauzug-Gurktal nappe systems, as well as in the Greywacke zone units with a dominating Variscan metamorphic imprint occur. In many cases they are transgressively overlain by unmetamorphosed or very-low grade metamorphic Permomesozoic sequences, whereas others experienced an additional Eo-Alpine overprint. Most of the units in the Koralpe-Wölz nappe system experienced a Permo-Triassic imprint and an Eo-Alpine overprint, which reached up to eclogite facies conditions. However, parts of the Wölz- and Radenthein Complexes show only the Eo-Alpine metamorphic imprint.

3. Tectonic overview

In the following a brief description of the different units as shown in Figure 2 will be given:

The **Tauern Window** (Fig. 3, units 32–35) exposes Penninic and sub-Penninic (European distal margin) units in the footwall of the Austroalpine nappe complex, which forms the hanging-wall plate during

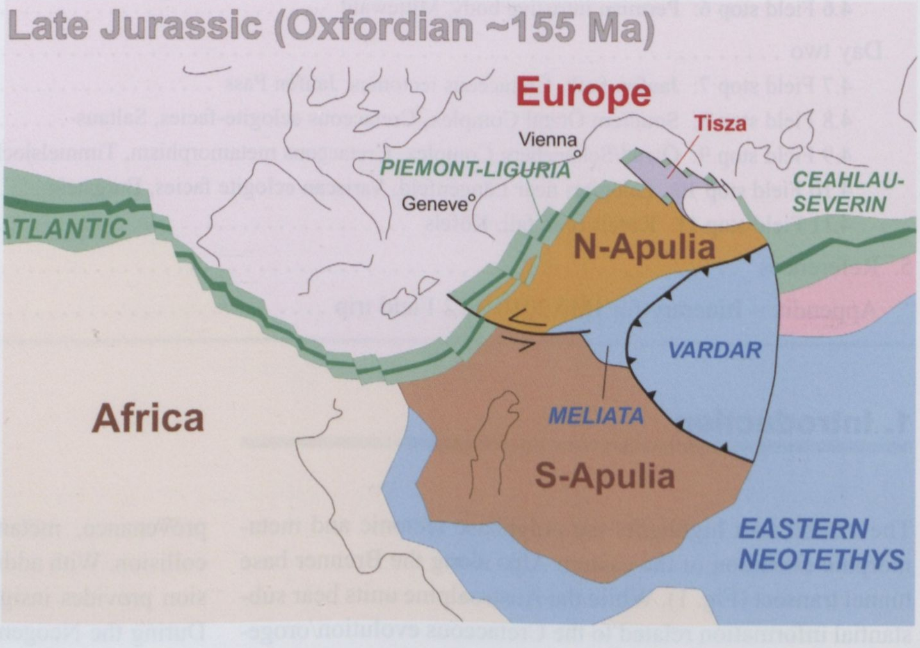

Fig. 2. Paleogeographical map displaying the relevant oceans for the Alps (after Schmid *et al.*, 2004).

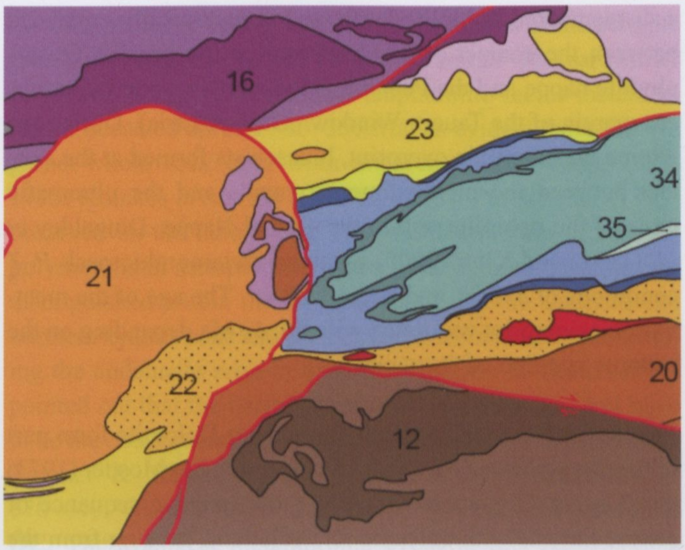

Fig. 3. Tectonic map of the Brenner area (from Schmid *et al.*, 2004): 12: upper crust Southern Alps; 13: post-Variscan cover Southern Alps; 16, 17, 18: Upper Austroalpine nappes (NCA and GWZ); 21: Upper Austroalpine basement nappe ÖC; 22: Upper Austroalpine basement nappe Texel complex; 23: Upper Austroalpine basement nappe (Campo, Innsbruck quartzphyllite); 24: Lower Austroalpine basement nappe; 26: Upper Penninic nappe; 32: Lower Penninic nappe; 33: Sub-Penninic: Mesozoic cover; 34: Sub-Penninic: non eclogitic basement; 35: Sub-Penninic: eclogitic basement.

Tertiary plate collision. The units within the Tauern Window are separated into several nappes that are characterized by typical lithofacial assemblages. From the footwall to the hangingwall, the nappe stack includes:

(1) The Venediger Nappe and the Wolfendom Nappe comprising a pre-Variscan basement intruded by Variscan granitoids (Zentralgneis cores) and a cover sequence of Jurassic metacarbonates, and Cretaceous metapelites and metapsammites.
(2) The Storz and Riffl Nappes comprising Variscan and Alpidic polymetamorphic basement rocks covered by the late Palaeozoic(?) or Cretaceous(?) metapelites and graphitic quartzites.
(3) The Eclogite Zone which is restricted to the central southern Tauern Window and which is characterized by a Mesozoic volcano-sedimentary sequence.
(4) The Rote Wand-Modereck Nappe, consisting of basement rocks which are covered by Permian to Triassic quartzites and Triassic metacarbonates, Jurassic breccias, calcareous micaschists and metatuffs as well as Cretaceous metapelites and metapsammites.
(5) The Glockner Nappe, which contains an oceanic basement (serpentinites and ultramafic rocks) and a partly incomplete ophiolithic sequence.
(6) The Matrei Zone, interpreted to represent an accretionary wedge, is characterized by metamorphic flysch sediments, breccias and olistolithes mainly of Austroalpine derivation.
(7) The Klammkalk Zone, consisting of calcareous schists, massive marbles and minor phyllites, forming a low-grade metamorphic equivalent to the 'Bündnerschiefer' in the Glockner Nappe.

These units are surrounded by the remnants of Lower Austroalpine units. The Eclogite Zone contains mafic eclogites of tholeiitic and slightly alkaline chemical composition (Miller, 1974, 1977, 1987). The protoliths are assumed to be basalts with an intra-plate character (Höck & Miller, 1987). They are often retrogressed to garnet-amphibolites and garnet-bearing greenschists due to a Barrovian-type, greenschist to amphibolite-facies overprint. The associated metasediments experienced the same high-pressure metamorphism (Franz & Spear, 1983; Dachs, 1986, 1990; Spear & Franz, 1986). The rocks exposed within the Eclogite Zone experienced a polyphase metamorphic evolution. Starting with inclusions in garnets, which are sometimes interpreted as pseudomorphs after lawsonite, a first stage of metamorphism at ca. 400 °C can be deduced (Miller, 1977, 1986; Frank *et al.*, 1981, 1987). Eclogite-facies metamorphism is only rarely documented and is only observed clearly in the Eclogite Zone. The eclogite-facies rocks were buried to a depth of at least 65 km (20 kbar, 600 °C; Holland, 1979; Dachs, 1986, 1990; Frank *et al.*, 1987a; Droop *et al.*, 1990; Selverstone *et al.*, 1992; Zimmermann *et al.*, 1994; Getty & Selverstone, 1994). On the other hand, the entire nappe pile of the Tauern Window was subsequently affected by pervasive blueschist-facies metamorphism with *P–T* conditions ranging from 7–15 kbar and ca. 450 °C (Raith *et al.*, 1980; Holland, 1979; Zimmermann *et al.*, 1994; Holland & Richardson, 1979; Selverstone *et al.*, 1992; Cliff *et al.*, 1985; Droop, 1985; Holland & Ray, 1985; Frank *et al.*, 1987; Selverstone, 1993). Finally, the entire nappe pile was affected by Barrovian-type upper greenschist to lower amphibolite-facies metamorphism (e.g., Frank *et al.*, 1987a; Selverstone, 1993). Phengite $^{40}Ar/^{39}Ar$ mineral ages of ca. 36–32 Ma (Zimmermann *et al.*, 1994) from the Eclogite Zone are interpreted to represent cooling ages subsequent to Eocene blueschist-facies metamorphism (Zimmermann *et al.*, 1994).

The **Innsbruck Quartzphyllite** (Fig. 3, unit 23) crops out between Mittersill in the east and Innsbruck in the west. It is typically a rather monotonous, fine-grained, greenish to grayish phyllitic schist, with the mineral assemblage muscovite + chlorite + albite + quartz ± calcite. Locally, garnet-bearing schists occur south of the Patscherkofel. It has been divided into three stratigraphical units consisting of Devonian carbonatic black shales, Silurian carbonatic-sericitic phyllites and Ordovician quartzphyllites and greenschists, however numerous transitions may be found (Haditsch & Mostler, 1982). Although most of the Innsbruck Quartzphyllites were affected by lower greenschist-facies metamorphism (Hoschek *et al.* 1980; Sassi & Spiess, 1992; Piber & Tropper, 2005), some central parts of the Innsbruck Quartzphyllite have been affected by middle greenschist-facies metamorphism (Kolenprat *et* *al.* 1999; Piber & Tropper, 2007). Geochronological investigations revealed a complex metamorphic history indicating a possible Permian- and Eo-Alpine overprint (Dingeldey *et al.*, 1997; Rockenschaub *et al.*, 1999; Handler *et al.*, 2000). Recently, a number of new results have been obtained concerning the internal structure of the Innsbruck Quartzphyllite (Kolenprat *et al.*, 1999). Large parts of the Innsbruck Quartzphyllite must therefore be considered as highly deformed, retrograde old (Variscan?) basement. These studies revealed a metamorphic zonation with garnet-free phyllites at the northern and southern rims and garnet bearing phyllites in the central part, thus reflecting a slightly higher grade of metamorphism in the center. This observation was interpreted in terms of a km-scale isoclinal fold of the Innsbruck Quartzphyllite (Schmidegg 1964, Rockenschaub 1998; Kolenprat 1998). Kolenprat *et al.* (1999) show, that the Innsbruck Quartzphyllite has a complex deformation history, with structures ranging from pre-Alpine (Variscan) to late Alpine (Neogene) in age. The pre-Alpine foliation is preserved only locally. During the Eo-Alpine orogeny, intensive mylonitization associated with W- to NW-directed nappe stacking, occurred. The Meso- and Neo-Alpine deformation is characterized by the imbrication of Austroalpine units as a consequence of N-directed thrusting of the Austroalpine nappes over the Penninic Units and subsequent exhumation of the Tauern-Window during N–S-shortening and E–W-extension (Kolenprat *et al.*, 1999). On top of the Innsbruck Quartzphyllite, two units occur in the vicinity of the Brenner base tunnel, namely the Patscherkofel Crystalline Complex and the Kellerjochgneiss.

The **Patscherkofel Crystalline Complex** (PCC) is part of the Austroalpine basement nappes north of the Tauern Window, which is tectonically located on top of the Innsbruck Quartzphyllite. The PCC is mainly composed of mica schists with the mineral assemblage plagioclase + muscovite + biotite + chlorite + quartz ± chloritoid ± garnet$_{1,2}$ ± ilmenite ± clinozoisite ± staurolite ± margarite. Garnet$_1$ + staurolite represent Pre-Alpine relicts, all other minerals are part of the Eo-Alpine mineral assemblage. Thermobarometric investigations of Piber *et al.* (2008) yielded temperatures between 510 °C and 570 °C and pressures ranging from 9.5 to 12.2 kbar for the samples from the PCC.

The **Kellerjochgneiss** or Schwaz Augengneiss is also part of the Austroalpine basement nappes north of the Tauern Window. The Kellerjochgneiss is a former I-type augengneiss and contains the mineral assemblage muscovite + plagioclase + chlorite + quartz ± biotite ± clinozoisite. It tectonically overlies the Innsbruck Quartzphyllite. Multiequilibrium calculations of samples of the Kellerjochgneiss yielded pressures ranging from 3.2 to 6.8 kbar and temperatures ranging from 285 to 345 °C (Piber, 2005).

The **Tarntal Nappe** (Fig. 3, unit 24) is a complex geologic unit, which consists of low-grade metamorphic sediments and a dismembered ophiolite body, and is tectonically emplaced between the contact of the Austroalpine Innsbrucker Quarzphyllite nappe and the Penninic Glockner Nappe at the northern margin of the Tauern Window (Tirol, Austria). During the Alpine metamorphic overprint, blueschists formed at the contact between the metasedimentary units and the ultramafic units of the ophiolite within the Tarntal Nappe. Dingeldey *et al.* (1997) and Klier (2005) obtained metamorphic peak *P–T* conditions of 350 °C and 8 to 10.5 kbar. The age of the metamorphic overprint was dated with 50–40 Ma depending on the tectonic position of the samples.

The Wildschönau Schists and the Schwaz Dolomite form part of the **Greywacke Zone** (unit 18). According to Mostler (1973) the Western Greywacke Zone is a stratigraphic sequence of metasediments with volcanic intercalations, ranging from the Ordovician to the Late Devonian. The Wildschönau Schists are composed of light gray phyllites similar to the Innsbruck Quartzphyllite. Roth (1983) characterized two different varieties of the Wildschönau Schists, the sandy type and the phyllitic type. The mineral assemblage of the Wildschönau Schists is very similar to the Innsbruck Quartzphyllites containing the mineral assemblage muscovite + chlorite + albite + quartz ± calcite. In the Western Greywacke Zone, modern thermobarometric data were lacking until recently. Based on index minerals, Hoschek *et al.* (1980) estimated lower greenschist-facies conditions for the Wildschönau Schiefer. Piber (2005) obtained *P–T* conditions of 4.5 kbar and 330 °C, based on multi-equilibrium thermobarometry on one sample of the Wildschönau Schists. Geochronological investigations by Handler *et al.* (2000) and Anglmeier *et al.* (2000) indicate a Permian metamorphic overprint. Using $^{40}Ar/^{39}Ar$ and $^{87}Rb/^{87}Sr$ recently yielded Eo-Alpine ages in the central Greywacke Zone of 102–98 Ma (Schmidlechner *et al.*, 2006) in addition to the $^{87}Rb/^{87}Sr$ ages of 137 to 127 Ma and $^{40}K/^{39}Ar$ ages of 113 to 92 and 113 to 106 Ma from the Greywacke Zone close to Zell am See which also give reasonable evidence for an Eo-Alpine metamorphic overprint around ca. 300 °C (Kralik *et al.*, 1987).

The **Ötztal Complex** (Fig. 3, ÖC, unit 21) is a large crystalline complex in the western part of the Austroalpine units. The ÖC consists of quartzofeldspatic and metapelitic metasediments with various intercalations of orthogneisses, amphibolites and rare metacarbonates. The oldest metamorphic event is "Caledonian" in age (460–490 Ma), leading to the formation of orthogneisses (Thöni, 1986) and scattered occurrences of migmatites (Söllner *et al.*, 1982; Söllner & Schmidt, 1981; Klötzli-Chowanetz *et al.*, 1997). Hoinkes (1973) estimated the *P–T* conditions of migmatite formation with 680 °C and ≥4 kbar, Thöny *et al.* (2008) obtained slightly lower pressures of <2.8 kbar. The Variscan metamorphic overprint ranges from 390–295 Ma (Thöni, 1999). The first stage of the Variscan event was a high-pressure metamorphism around 373–359 Ma, leading to the formation of eclogites in the central part of the ÖC (Miller & Thöni, 1995). The conditions of the eclogite facies were estimated to be 710–750 °C and 27–28 kbar (Miller & Thöni, 1995). The dominant amphibolite facies metamorphism occurred around 330–350 Ma, as evident from Sm-Nd garnet-whole rock ages from micaschists (Schweigl, 1993, 1995; Hoinkes *et al.*, 1997; Thöni, 1999). Purtscheller (1969) observed on the basis of the regional distribution of Al_2SiO_5 polymorphs in metapelites a systematic regional zonation and distinguished within the ÖC two zones: (1) the southern and northern kyanite zone and (2) the central sillimanite zone including the andalusite zone in the west. Hoinkes & Thöni (1993) pointed out that the occurring mineral zonation does not have to be the consequence of a single Variscan metamorphic event. Tropper & Hoinkes (1996) estimated *P–T* conditions of 570–640 °C and 5.8–7.5 kbar for the northwestern part of the ÖC. The youngest metamorphic event in this Austroalpine basement occurred during the Cretaceous Eo-Alpine orogeny (100–73 Ma, Thöni, 1981; Thöni, 1999; Exner *et al.*, 2001; Habler *et al.*, 2001). The intensity of the Eo-Alpine overprint varies within the ÖC and increases from NW (lower greenschist facies) to SE (epidote-amphibolite facies) and reaches 550–600 °C and ≥11 kbar in the Schneeberg Complex (Hoinkes *et al.*, 1991; Konzett & Hoinkes, 1996). This zonation ends abruptly at the Passeier – Jaufen Line. This leads also to resetting of Variscan cooling ages from the NW to the SE (Thöni 1981; Thöni, 1999). To the south of the Passeier–Jaufen Line, in the Meran–Mauls basement (MMB) only a weak Eo-Alpine metamorphic overprint can be detected (Spiess, 1995).

The Paleozoic **Schneeberg Complex** (SC) consists of at least three narrow and structurally complicated synclines folded into the southern part of the polymetamorphic ÖC. The metasediments of the SC are characterized by the frequent presence of metamarls and marbles as opposed to the ÖC where such lithologies are missing with few exceptions known from the central ÖC (Hoinkes & Thöni, 1993). Sölva *et al.* (2001, 2005) define the SC as a tectonic unit associated with the Schneeberg normal fault zone, separated from the ÖC and strongly affected by the Eo-Alpine tectonometamorphic event. Most recently, the discovery of Eo-Alpine andalusite coexisting with staurolite + biotite + garnet at temperatures ≥540 °C places tight constraints on the retrograde part of the Eo-Alpine *P–T* path of SC rocks that is characterized by an almost isothermal decompression from the peak of metamorphism into the andalusite stability field. SC rocks do not provide any evidence for an earlier, high-pressure stage. Geochronologic results by Elias (1998) and Fügenschuh *et al.* (2000) point to a rapid uplift and exhumation of both SC and underlying ÖC after the peak of metamorphism. According to Fügenschuh *et al.* (2000) initial uplift rates were around 1 mm/year starting around 90 Ma, which decreased to values of 0.2 to 0.7 mm/year (Hoinkes *et al.*, 1991).

The Variscan basement of the **Southalpine domain** (Fig. 3, unit 13) is confined to the west and north by the Periadriatic (Giudicarie line and Pustertal line) fault system. In the southeast, small basement outcrops within the Cenozoic molasse deposits of the Po Plain occur. Most of the basement is comprised of monotonous quartzphyllites (Brixen Quartzphyllite), which were pervasively affected by the Variscan metamorphic and tectonic overprint. Due to its now slightly tilted position, the basement shows a metamorphic gradient, which increases from southeast towards northwest (Sassi & Spiess, 1993). In the area of Toblach, the basement contains the mineral assemblage quartz + chlorite + white mica + albite and represents the lowest peak metamorphic conditions of the basement with temperatures of 350–400 °C and a pressure of ca. 0.4 GPa. The metamorphic conditions increase towards the northwest and reach maximum *P–T* conditions in the area of Brixen/Bressanone. In this area the basement contains the mineral assemblage quartz + biotite + chlorite + white mica + garnet + albite + plagioclase and calculated *P–T* conditions based on garnet-biotite thermometry and plagioclase–biotite–garnet–muscovite barometry yielded temperatures of 450–550 °C and pressures of 0.5–0.65 GPa (Ring & Richter 1994).

In the Southalpine domain the **Permian intrusive complexes** of the Brixen granite, Ifinger granodiorite and Kreuzberg granite cover an area of ~250 km² and are thought to have been the result of the collapsing Variscan orogenic belt, which led to the formation of large extensional terrains (Acquafredda *et al.*, 1997; Bargossi *et al.*, 1981; Bargossi *et al.*, 1998; Del Moro & Visona, 1982). Although these intrusive complexes were already mapped (Del Moro & Visona, 1982) and considerable literature concerning their magmatic evolution already exists (Bonin *et al.*, 1993; Schuster *et al.*, 2001; Dal Piaz & Martin, 1998) almost no petrological (Bonin *et al.*, 1993; Aquafredda *et al.*, 1997) and only few geochronological data (Bonin *et al.*, 1993; Borsi *et al.*, 1972; Rottura *et al.*, 1998) are available so far. The investigated intrusions namely the Brixen/Bressanone granodiorite, the Ifinger/Ivigna granite and the Kreuzberg/Monte Croce granite are all aligned along the Periadriatic Lineament. The major part of the Brixen granite is granitic to granodioritic in composition with the mineral assemblage K-feldspar + plagioclase + biotite + quartz + accessories (zircon, apatite, ilmenite ± monazite). Zircon ages from three intrusions in the Southalpine basement show ages ranging from 293 ± 12 Ma (Kreuzberg granite), 289 ± 6.1 Ma (Ifinger granodiorite) to 278 ± 12 Ma (Brixen granite). These geochronological data seem to indicate a rejuvenation trend from south-west to north-east which might be evidence for a plane motion of the north-western realm of the Athesian Volcanic Group (AVG) caldera during the late Variscan orogeny collapse (Thöny, 2008).

4. Field stops

Day one

4.1 Field stop 1: Entrance of the Brenner base tunnel in Innsbruck, Sillschlucht

Located at the southern limit of Innsbruck directly under the ski jump stadium this stop allows to discuss the local geology in the area of the northern entrance of the Brenner base tunnel (Fig. 4). The outcrops are located along a small track near the river Sill. Apart from unstable Quaternary deposits, giving rise to mobility right at the tunnel entrance, the local geology is dominated by quartzphyllite. Metamorphosed under lower greenschist-facies conditions during the Variscan cycle the rocks show multiphase tectonic overprint from ductile deformation during pre-Alpine and Alpine times to Neogene brittle deformation. Second phase folding led to the formation of a large recumbent fold, which has granitic basement in its core. Although rather monotonous, different lithologies can be observed along the track, ranging from porphyries to amphibolites/prasinites to marbles. According to the overall appearance the quartzphyllite unit most likely represents a metamorphosed turbidite sequence.

4.2 Field stop 2: Cataclasites of Brenner fault zone, Stefansbrücke

Some 5 km south of Innsbruck along the federal road to Brennerpass brittle fault rocks related to the Brenner Fault Zone are outcropping in an abandoned quarry. The tectonically overprinted host rock is the basement of the ÖC, various stages of brittle deformation can be studied. While the least deformed part still displays the original features (schistosity, folds in paragneiss) deformation intensity increases to finally expose a fault gouge. Depending on the outcrop conditions (due to the brittle deformation the are very erodable) shear sense criteria pointing to top to the west kinematics can be observed (Fig. 5). Several similar outcrops of fault gouge in the wider Brenner area have been sampled by Zwingmann & Mancktelow (2004) for conventional K/Ar dating of clay minerals. While most of the samples yielded Neogene ages, in accordance with the brittle faulting along the BFZ, the samples from this outcrop are dominated by Cretaceous ages. This clearly points to inherited information from the overwhelming Cretaceous metamorphic overprint within the ÖC.

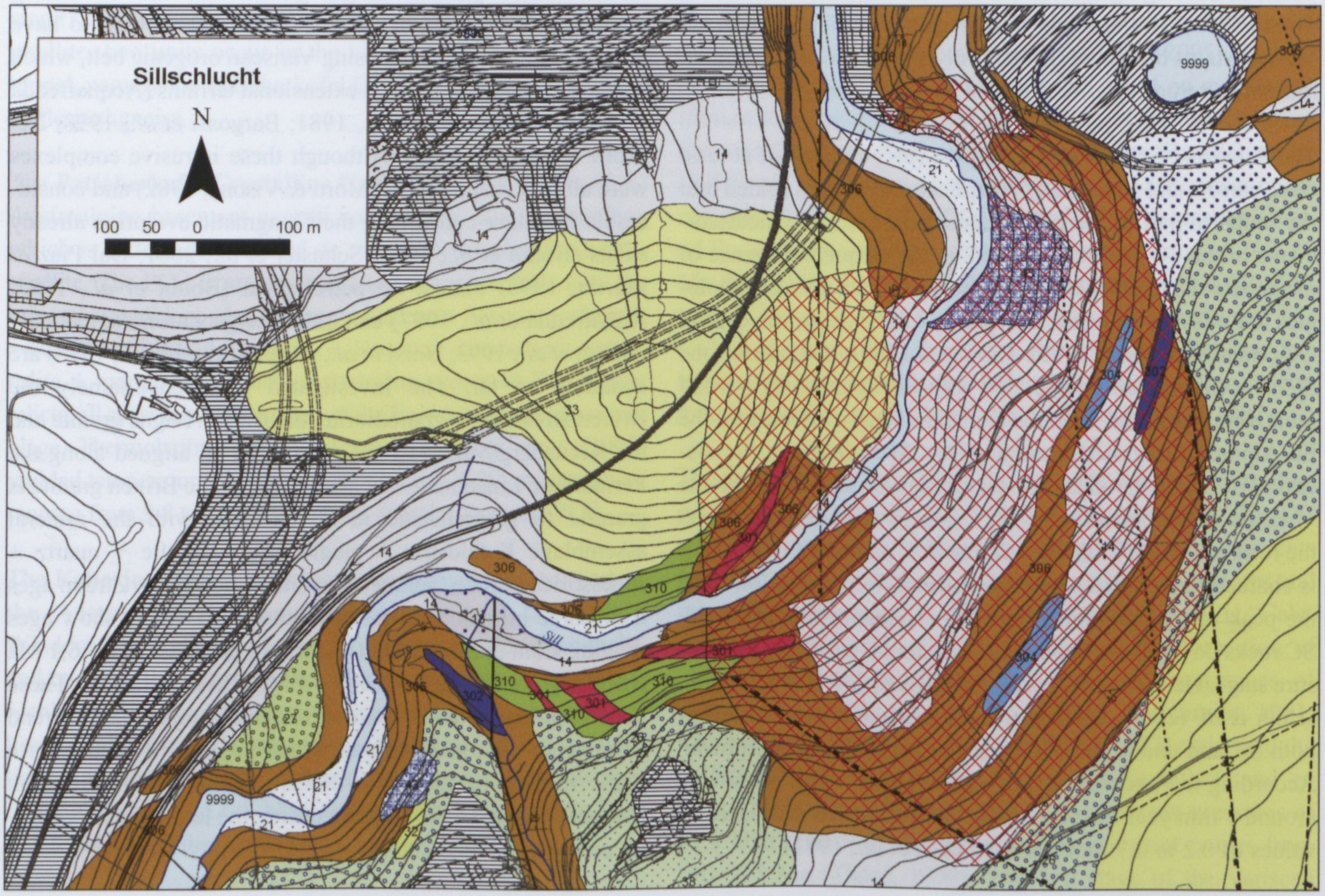

Fig. 4. Detailed geological map of the northern entrance of the Brenner base tunnel (Brandner *et al.*, 2008). Hatched area: rock slide; brown: quartzphyllite; red: porphyry; green: prasinite; blue: marbles.

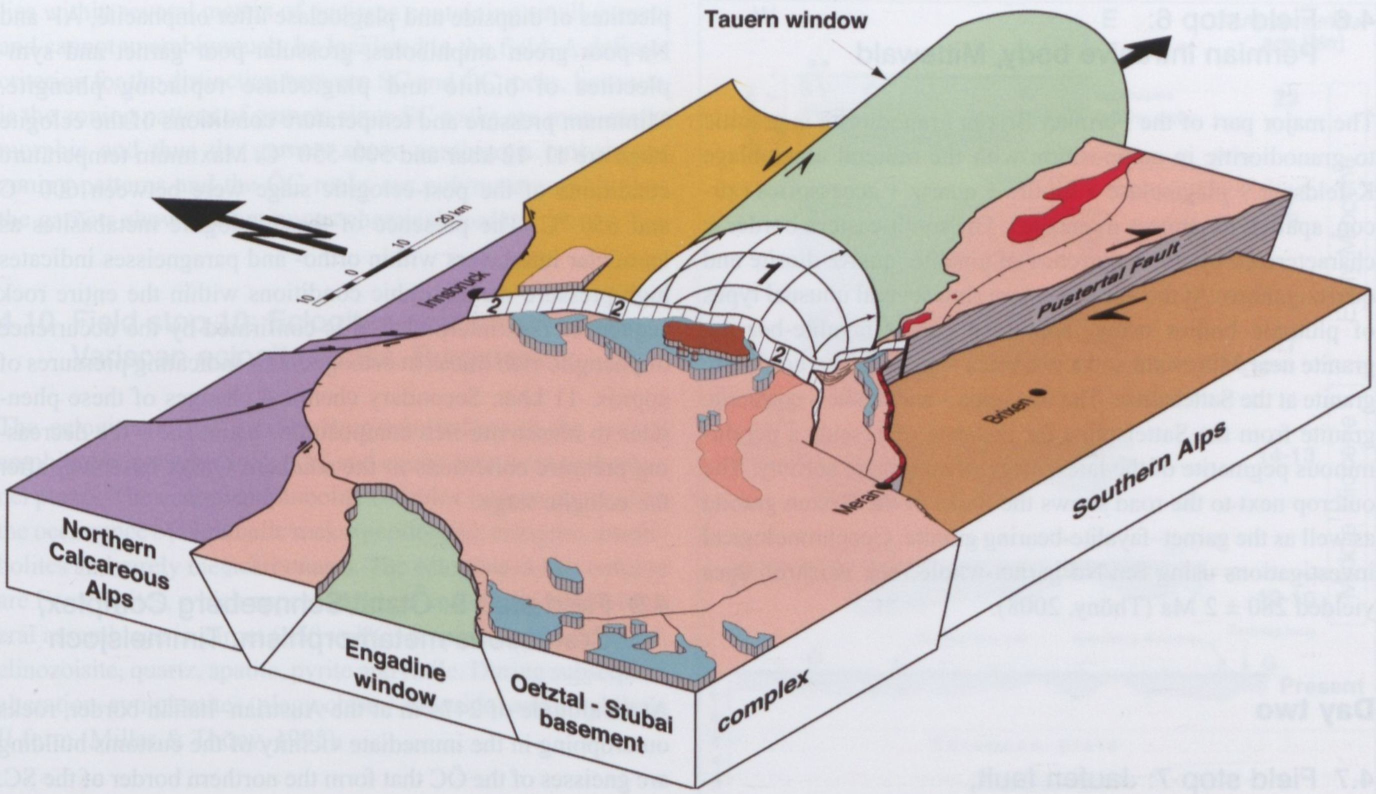

Fig. 5. Simplified block diagram illustrating the Brenner fault zone and the involved units (Fügenschuh *et al.*, 1997).

4.3 Field stop 3: Overview of regional geology, Nösslach

This overview stop is located south of the village of Steinach along a side road close to the highway exit Nösslach. If the weather is fine this stop offers a beautiful overview into the local nappe pile, exposing, from bottom to top, Zentralgneiss, Schieferhülle, Tarntaler Mesozoic, Innsbrucker Quartzphyllite, Northern Calcareous Alps, Ötztal Stubai Complex and Steinacher nappe. It is also from this point that you can judge the substantial amount of tectonically omitted material due to normal faulting along the BFZ (Fig. 5).

4.4 Field stop 4: Brenner fault mylonites, Zentralgneiss, Brenner Pass

From the Brenner Pass on the Austrian side a small paved road brings us up to an active quarry in the Zentralgneiss. Along the road highly mylonitized rocks of the upper Schieferhülle (Bündnerschiefer) with beautiful shear sense criteria can be observed. In the quarry the Permian Zentralgneis is tectonically overlain by Mesozoic strata including the limestone mylonites of the Hochstegen formation. The granitic gneiss is exposed in the core of a major WSW–ENE trending antiform, related to Tertiary nappe piling and overprinted by Neogene normal faulting (Fig. 6). Deformation within the granite is varying; ranging from almost undeformed to strongly flattened. This allows for a guess on the width of the BFZ shear zone on the order of 1-2 km. Apart from magmatically zoned feldspars various enclaves and xenoliths can be studied.

4.5 Field stop 5: Periadriatic line, Oligocene intrusive body, Mauls

In the village of Mauls (south of Sterzing) we follow a paved road towards the east entering a small valley. In the riverbed of the "Nöckebach" we can touch the contact between the metamorphosed Austroalpine basement and the unmetamorphosed southern Alpine basement together with a small Oligocene tonalite body. This part of the Periadriatic fault, a first order fault system in the Alps, does not, as elsewhere, represent the suture between Europe and Adria but forms a repeatedly activated fault zone which originally might have formed the retrowedge of the Cretaceous orogen. The outcrop is of prime importance for the construction of the Brenner base tunnel since this tectonic zone will be crossed. On the surface it has a clear brittle character yet mylonites can definitively be expected at somewhat deeper levels. Due to its rather vertical dip it is not monitored in the seismic Transalp section which gave rise to rather provocative models. This part of the Periadriatic fault system is furthermore of great importance for solving the question of an originally straight vs. an already curved fault zone.

4.6 Field stop 6: Permian intrusive body, Mittewald

The major part of the Permian Brixen granodiorite is granitic to granodioritic in composition with the mineral assemblage K-feldspar + plagioclase + biotite + quartz + accessories (zircon, apatite, ilmenite ± monazite). The south-eastern border is characterized by the occurrence of tonalite, quartz-diorite and quartz-gabbro. At the north-western rim, several unusual types of plutonic bodies occur, namely a garnet–fayalite-bearing granite near Mittewald and a two mica – andalusite – cordierite granite at the Sattelspitze. The two mica – andalusite – cordierite granite from the Sattelspitze for instance represents a peraluminous pegmatite of the latest stage of magmatic activity. The outcrop next to the road shows the rocks of the Brixen granite as well as the garnet–fayalite-bearing granite. Geochronological investigations using Sm/Nd garnet-whole rock isochron ages yielded 280 ± 2 Ma (Thöny, 2008).

Day two

4.7 Field stop 7: Jaufen fault, Cretaceous tectonics, Jaufen Pass

From Sterzing a spectacular road climbs up towards west to the Jaufen Pass. The road roughly follows the Jaufen fault zone, separating Cretaceous metamorphic Astroalpine basement (ÖC) from Austroalpine units which lack substantial metamorphic overprint (Meran–Mauls Basement). Across the fault zone a jump in cooling ages occurs from Cretaceous in the NW to Variscan in the SE. Thus the fault has to have a Cretaceous history. Yet recent studies (Viola *et al.* 2004; Pomella *et al.*, 2008) revealed a polyphase history, the last activity of which occurred in the course of normal faulting along the BFZ. Along the road metamorphic basement of the ÖC as well as the Meran–Mauls basement can be studied together with some outcrops of Jaufen fault mylonites.

4.8 Field stop 8: Southern Ötztal Complex, Cretaceous eclogite-facies, Saltaus

In this locality there is an outcrop of a few m in size along a forest track that branches off the main road from St. Martin – Meran approx. 3 km to the south of St. Martin. Metabasites of the southern Ötztal Complex hitherto mapped as amphibolites, were identified as eclogites in this outcrop. Primary mineral parageneses are tschermakitic to pargasitic green amphiboles, omphacite, garnet, phengite, zoisite, rutile and quartz. Al-pargasite forms between garnet and omphacite and is interpreted as a retrograde reaction product. In addition, retrogression of the eclogitic parageneses reflecting decreasing pressure and increasing temperature conditions are the formation of symplectites of diopside and plagioclase after omphacite, Al- and Na-poor green amphiboles, grossular-poor garnet and symplectites of biotite and plagioclase replacing phengite. Minimum pressure and temperature conditions of the eclogite stage are 11–12 kbar and 500–550 °C. Maximum temperature conditions of the post-eclogitic stage were between 600 °C and 650 °C. The presence of these eclogitic metabasites as lenticular interlayers within ortho- and paragneisses indicates high-pressure metamorphic conditions within the entire rock sequence. This interpretation is confirmed by the occurrence of phengite-rich micas in orthogneisses indicating pressures of approx. 11 kbar. Secondary chemical changes of these phengites to muscovite-rich compositions again show the decreasing pressure conditions in the southern Ötztal basement after the eclogite stage.

4.9 Field stop 9: Ötztal/Schneeberg Complex, Cretaceous metamorphism, Timmelsjoch

At an altitude of 2474 m at the Austrian–Italian border, rocks outcropping in the immediate vicinity of the customs building are gneisses of the ÖC that form the northern border of the SC. The gneisses were affected by both Variscian and Eo-Alpine metamorphism: The Variscan metamorphism reached conditions of the amphibolite facies which led to the formation of an assemblage plagioclase + biotite + muscovite + garnet + quartz ± staurolite ± kyanite. The subsequent Eo-Alpine event in this area reached *P–T* conditions slightly below the stability of staurolite. This caused a retrogressive breakdown of staurolite to paragonite + chlorite + quartz. This reaction caused the formation of mica + chlorite + quartz pseudomorphs after lath-shaped staurolite crystals that may reach several cm in length and can be found on cleavage planes. *P–T* conditions sufficient for Eo-Alpine staurolite formation, however, were reached within the northernmost part of the SC.

On the Italian side at an altitude of 2200 m, after the second 180° road turn, the northern border of the main syncline of the SC towards the underlying ÖC is exposed along the roadside over a distance of approx. 100 m. At this location the distinction between both units is unambiguous due to the difference in lithologies since the rocks of the ÖC are monotonous gneisses with abundant small (≤1 mm) garnet and biotite and the rocks of the SC are garnet-micaschists with large (0.5 to >1 cm) garnets as well as amphibole-bearing rocks with large amphiboles (≥1 cm). The SC rocks exposed belong to the marginal series ("bunte Randserie") of intercalated garnet-micaschists, amphibolites, hornblende garbenschists, marbles and quartzites that delimit the main syncline of the SC. Further downhill, rocks of the central SC main syncline are encountered that are characterized by rather monotonous garnet-micaschists ("monotone Serie"). The SC-ÖC boundary is located a few meters uphill from a quartzite band that can unambiguously be assigned to the SC. The actual boundary lies within several meters of gneisses containing small garnets and cannot unambiguously be localized in the field. A definite criterion for the distinction between SC and ÖC rocks, however, is the zoning pattern of garnets since SC rocks are monometamorphic and thus the garnets show continuous bell-shaped zoning patterns and the ÖC rocks are polymetamorphic thus the garnets show discontinuous chemical zoning.

4.10 Field stop 10: Eclogites near Längenfeld, Variscan eclogite facies, Burgstein

The eclogites at the locality Burgstein belong to the central amphibolite complex in the ÖC and can be seen next to the tunnel portal. The central amphibolite complex is characterized by the occurrence of ultramafic rocks (peridotites), eclogites, amphibolites and rarely metacarbonates. The eclogites in this outcrop are Fe-eclogites, which appear dark-red and massive. The mineral assemblage is garnet (>50 vol%), omphacite, amphibole I, clinozoisite, quartz, apatite, pyrite and rutile. During subsequent alteration, symplectites (plagioclase + diopside) and amphibole II form (Miller & Thöny, 1995).

4.11 Field stop 11: Köfels rock fall, Köfels

The Köfels rockslide is the biggest one in the Alps within basement rocks. It involved augengneisses of granitic composition as well as paragneisses. With a total mass of 3.2 km^3 of material (Brückl *et al.*, 2001) the rockslide was able to fill up the valley by some 100 meters. Due to the formation of a dam up to 100 m thick fluvio-lacustrine sediments were deposited in the Längenfelder basin (Heuberger, 1966, 1975). Relative, ^{14}C and cosmogenic isotope dating of exposed surfaces yielded an age of ~ 9800 cal BP for its activity (Ivy-Ochs *et al.*, 1998). After the main event at least one smaller event followed. The Köfels rockslide is well known for its frictionite, a pumice rock formed in the context of frictional melting (Erismann *et al.*, 1977).

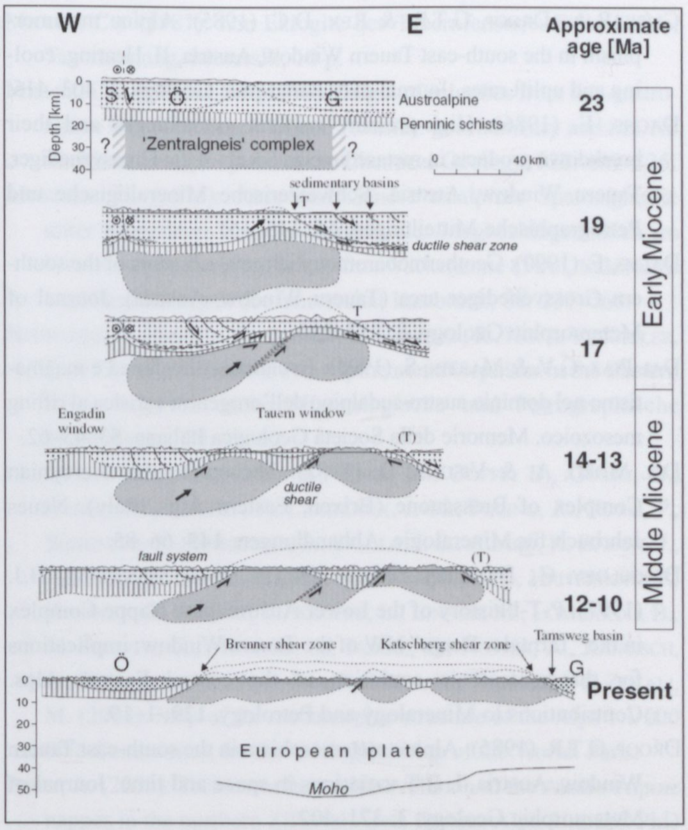

Fig. 6. Formation of the Tauern Window from the Early Miocene to the present (after Frisch *et al.,* 2000). Note that the sections are in E–W orientation.

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Appendix – Itinerary for IMA2010 AT2 Field trip

Thursday, August 19, 2010 (Day 1). Transect through the Eastern Alps (deformational focus)

06.00–13.00	Travel to Innsbruck and lunch
13.00–14.00	Field stop 1: Sillschlucht: introduction to geological background
14.00–16.00	Field stops 2, 3 and 4: Stefansbrücke, Nösslach, Brenner, Brenner fault zone
16.00–17.00	Field stops 5 and 6: Franzensfeste, Mauls, Permian and Oligocene intrusions
	Accomodation in Sterzing

Friday, August 20, 2010 (Day 2). Transect through the Eastern Alps (metamorphic focus)

09.00–10.00	Field stop 7: Jaufen pass, Cretaceous tectonics
10.00–11.00	Field stop 8: Saltaus, Cretaceous eclogite-facies metamorphism
11.00–12.00	Field stop 9: Timmelsjoch: Ötztal Complex, Schneeberg Complex
12.00–13.00	Lunch break at the Timmelsjoch
13.00–14.00	Field stop 10: Burgstein: Variscan eclogites
14.00–15.00	Field stop 11: Köfels, rock fall
15.00–22.00	Travel to Budapest

USEFUL NOTES

INSTRUCTIONS FOR AUTHORS

General

Acta Mineralogica-Petrographica (AMP) publishes articles (papers longer than 4 printed pages but shorter than 16 pages, including figures and tables), notes (not longer than 4 pages, including figures and tables), and short communications (book reviews, short scientific notices, current research projects, comments on formerly published papers, and necrologies of 1 printed page) dealing with crystallography, mineralogy, ore deposits, petrology, volcanology, geochemistry and other applied topics related to the environment and archaeometry. Articles longer than the given extent can be published only with the prior agreement of the editorial board.

In the form of two subseries, AMP publishes materials of conferences (AMP Abstract Series) and field guides (AMP Field Guide Series), or, occasionally supplement issues related to other scientific events.

The journal accepts papers that represent new and original scientific results, which have not appeared elsewhere before, and are not in press either.

All articles and notes submitted to AMP are reviewed by two referees (short communications will be reviewed only by one referee) and are normally published in the order of acceptance, however, higher priority may be given to Hungarian researches and results coming from the Alpine-Carpathian-Dinaric region. Of course, the editorial board does accept papers dealing with other regions as well, let they be compiled either by Hungarian or foreign authors.

The manuscripts (prepared in harmony of the instructions below) must be submitted to the Editorial Office in triplicate. All pages must carry the author's name, and must be numbered. At this stage (revision), original illustrations and photographs are not required, though, quality copies are needed. It is favourable, if printable manuscripts are sent on disk, as well. In these cases the use of Microsoft Word or any other IBM compatible editing programmes is suggested.

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The abstract has to be followed by 4 to 10 keywords.

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When compiling the paper an Introduction – Geological setting – Materials and Methods – Results – Conlclusions structure is suggested.

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Bakker, R.J. (2002): http://www.unileoben.ac.at/~buero62/minpet/Ronald/Programs/Computer.html. Accessed: June 15, 2003.

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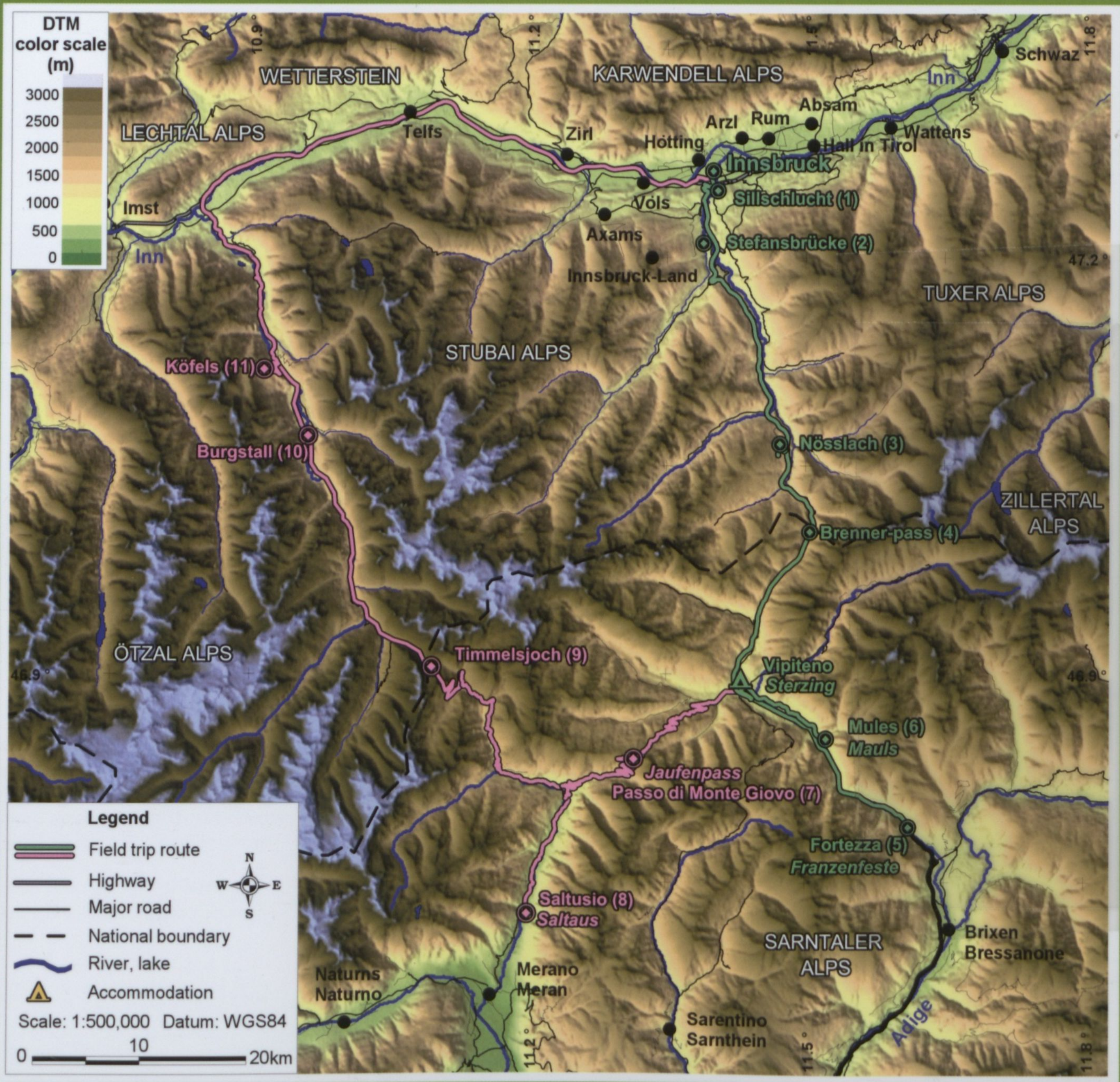

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